

plus b), an interior/exterior coupling loss of about 6 dB when the terminal is above the duct and about 10 dB or more when the terminal is below the duct [Dougherty and Hart, 1979].

In order for a wave trajectory drawn from a point below a duct to be trapped within a horizontally uniform duct, the trajectory must have a grazing incidence from below at the duct base elevation  $h_b$ . Therefore, unless the elevated duct is bounded below by another ducting layer, it appears that trapping of a wave trajectory (from below the duct) would require either a discontinuity in the duct or a tilt in the duct base; a wavy structure is a feature not uncommon in elevated ducts [Gossard, 1962; Gossard and Richter, 1970; Bean et al., 1971]. A recent experimental study observed that efficient coupling into (and out of) an elevated duct was associated with an unspecified periodicity in the duct structure [Crane, 1980]. A later section will apply the foregoing expressions in a specific example.

There are additional losses in duct propagation attributable to discontinuities in the duct structure and to other atmospheric conditions, such as the frequency-and-time-dependent absorption by the gaseous atmosphere [CCIR, 1978e; 1978f].

### 3. LAYER AND DUCT CHARACTERISTICS

In the case of layer-reflected modes and ducted modes of propagation, either as inhibitors of service fields or as enhancers of interference fields, the basic requirement is the presence of tropospheric layers of sufficiently strong (i.e., ducting) gradients. Given their presence, the efficiency of propagation associated with these layers is determined by their positioning ( $h_b$ ,  $h_o$ ,  $h_a$ ) relative to the telecommunication terminals and their trapping frequency relative to the telecommunication system's transmission frequency.

#### 3.1 Occurrence of Surface Ducts

The occurrence of refractivity gradients averaged over the first 100 meters above the surface has been described from historical meteorological data on a worldwide basis [Bean et al., 1966]. More recently, additional data have become available for selected areas, notably the northern hemisphere [Samson, 1975], Canada [Segal and Barrington, 1977], and India [Majumdar et al., 1977]. From these data, we can take the occurrence of initial gradients ( $dN/dh < -157$  N units/km) as direct measures of the occurrence of ground-based ducts that are 100 meters thick. Of course, the dependence upon surface reflections (and increased propagation loss) in such ducts will not be clear, since the strong ducting gradient may have occurred either at the surface or slightly elevated within that initial 100 meters. On overwater paths, the distinction has usually been maintained; some ocean areas have been extensively mapped for the probability of long-distance propagation via shallow evaporation ducts

or via the deeper advection ducts with slightly elevated layers [Dougherty and Hart, 1976].

There are some uncertainties associated with these ground-based ducts, especially those observed at the many recording stations on land. The widespread simultaneous observation of ducts over land does not mean necessarily, that these ducts are horizontally extensive (i.e., continuous) unless the terrain is approximately flat. The larger-scale irregularities of terrain (hills, cities, etc.) tend to modify the characteristics and limit the continuity or horizontal extent of ducts over land. Sea-surface ducts tend to be more prevalent and extensive than those over land, although there is some evidence that ocean depth and ocean currents can limit their horizontal extent. Nevertheless, although individual ducts are of finite length, there is little physical justification for an abrupt specific limit to horizontal duct dimensions. The limit has to be statistically defined, perhaps also varying with climatology and geographical locations, for which there are inadequate data at present for the limits of either overland or oversea surface ducts.

### 3.2 Occurrence of Elevated Ducts

Descriptions of elevated layer statistics are also available worldwide [Bean et al., 1966; Cahoon and Riggs, 1964] and for selected locales [Dougherty et al., 1967; Hall and Comer, 1969; Segal and Barrington, 1977; Ortenburger et al., private communication]. These provide annual and/or worst-month summaries for the occurrence of ducting and/or superrefractive elevated layers and/or their associated elevated duct parameters ( $dN/dh$ ,  $\delta M$ ,  $\delta h$ ,  $h_b$ ,  $h_o$ ,  $D$ ,  $f_t$ , etc.), all based upon historical radiosonde data. Figure 8 is a contour map for the United States, of the occurrence of elevated ducts as a percent of an average year, but based on only five years of radiosonde data. Except for the California Coast, the higher values of percent occurrence of elevated ducts (i.e., elevated layers with ducting gradients) is more common in the eastern half of the United States.

Figure 9 is a similar presentation except the occurrence is the percent of the worst months. The worst month is the month with the highest occurrences of elevated ducts. For most of the Nation, the worst month occurs in the summer, midsummer in West, late summer in the East. Along the Gulf Coast, the worst month occurs in the Spring. There are exceptions to these broad generalities. The worst month occurs in the Fall in the great basin (centered on Nevada and the desert portions of California, Arizona, and Utah) and in northwest Florida and the southern portions of Georgia, Alabama, and South Carolina.

Since these data are deduced from radiosonde measurements of the vertical structures of atmospheric temperature and humidity, they carry some limitations not appli-

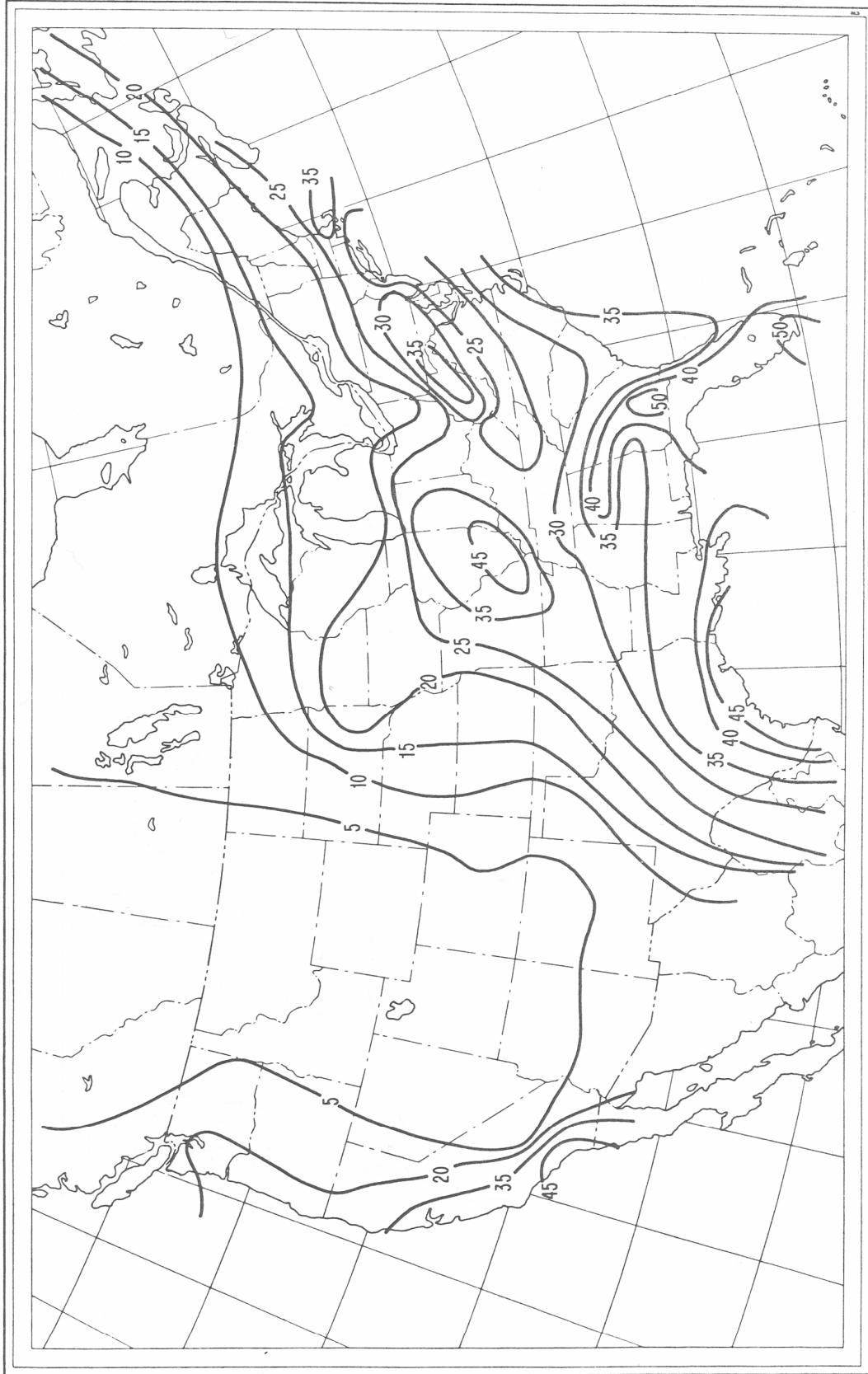


Figure 8. The occurrence of elevated ducts in percent of all hours of the year.

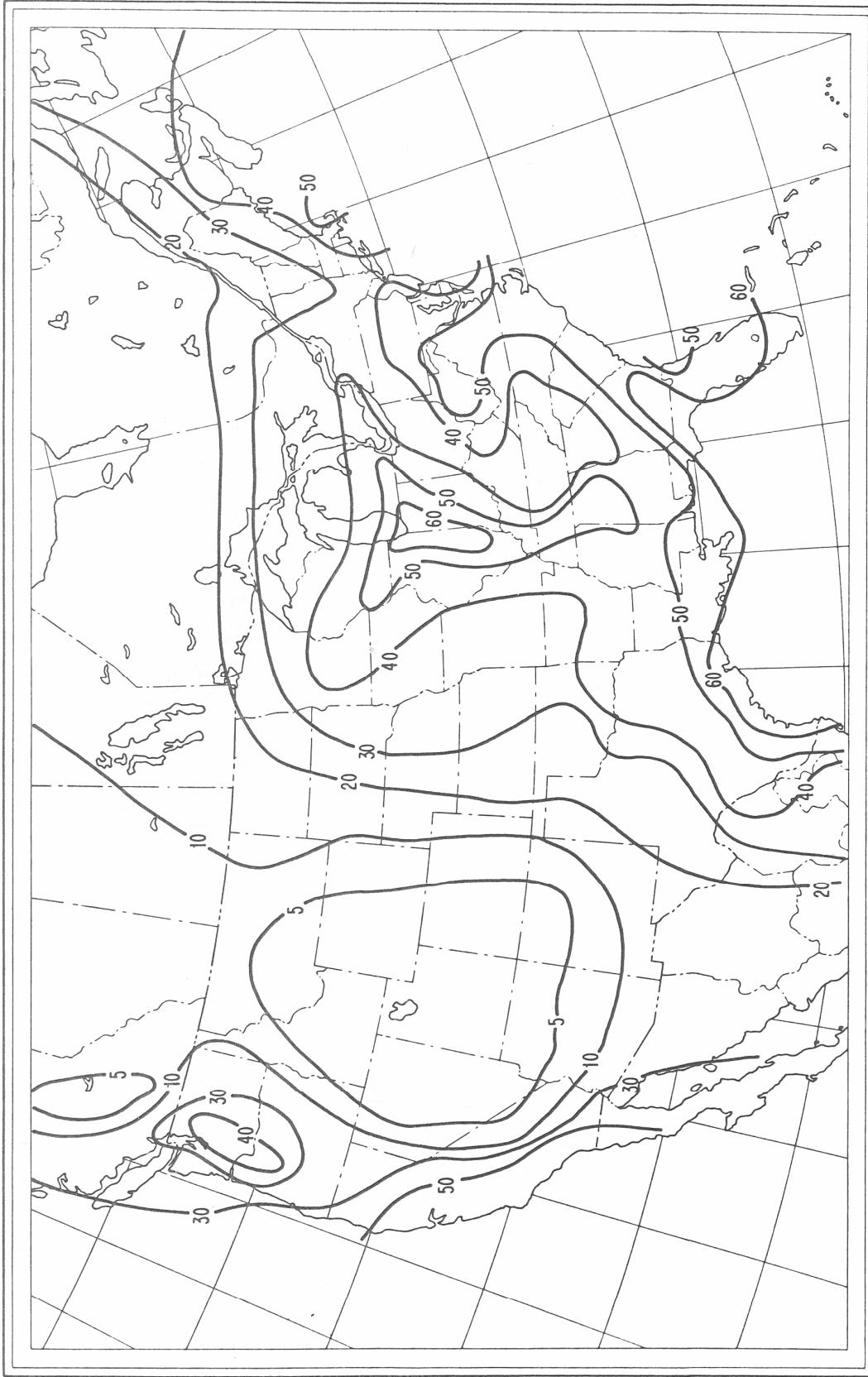


Figure 9. The occurrence of elevated ducts in percent of all hours of the worst month. For no month of the year would the expected occurrence of elevated ducts exceed the indicated values.

cable to the raw data. For example, the radio meteorologist is concerned with the vertical refractivity structure on a much finer scale than is of interest to the (non-radio-) meteorologist who collects the data. The radiosonde instruments' sensor response times and their sequential measure of temperature and humidity, although adequate for the National Weather Service's interests, do cause an overestimation of the elevated layer's thickness and an underestimation of its refractivity gradients [Bean and Cahoon, 1961; Bean and Dutton, 1961]. Since a gradient  $dN/dh < -157$  N units/km is evidence of an elevated duct, systematic underestimation means that ducting gradients occur somewhat more frequently than would be deduced from the data. Crane (1980) reported that the observation of ducts by radar surveillance was more frequent than indicated by radiosonde data. Similarly, the transition frequency, deduced through (7) from estimates of  $D$  in (6), is somewhat erroneous because of overestimates of  $\delta h$  and underestimates of  $(dN/dh)_0$ .

There is another disadvantage of estimating the occurrence of elevated ducts from historical meteorological data. Radiosonde data are usually collected twice a day (at 1200 and 2400 GMT) which may or may not correspond to the most favorable time of the day for the occurrence of ducts at each location. The data may, therefore, either overestimate or underestimate the day-by-day occurrence of ducts. Despite these disadvantages, their corrections could be estimated from additional effort and data so that the large body of historical data would still be useful. For example, identification of the sensor types will permit a correction in the estimates of the layer gradient and thickness [Dougherty et al., 1967]. Correlation of radiosonde historical data at certain locations with direct refractometer data obtained nearby [Bean, 1979] would permit estimated corrections for the occurrence of layers and some of their spatial variation.

### 3.3 Elevated Duct Statistics

Figure 10 locates the 107 radiosonde stations in the contiguous United States and nearby portions of Mexico and Canada that constituted the sources of the five-year data base for the elevated duct statistics [Ortenburger et al., private communication].

Figure 11 is a contour map of the median minimum trapping frequency,  $f_t(50\%)$ , for the elevated ducts. This was based upon (7) and the median duct thickness data,  $D(50\%)$ . Although the  $f_t(50\%)$  values are usually UHF, they are in the upper VHF range along the Gulf coasts and coasts of southern California and Florida. Of course, the duct thicknesses vary; the range of the resulting  $f_t$  values is indicated by the additional contour maps of  $f_t(10\%)$  and  $f_t(90\%)$  in Appendix B.

Figure 12 is a contour mapping of the optimum coupling elevation expected for 50% of elevated ducts. For example, the optimum coupling elevation (i.e., the

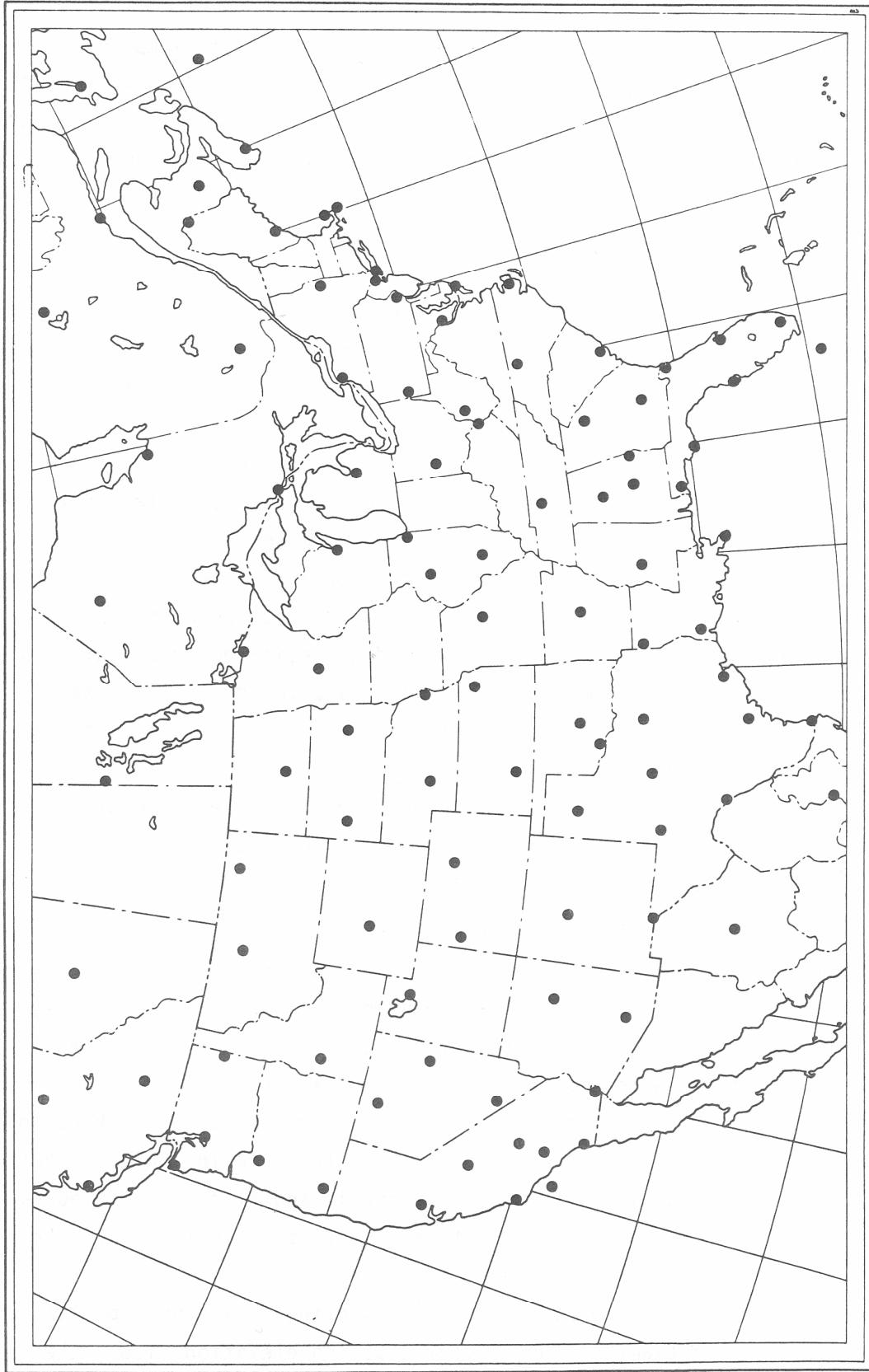


Figure 10. The locations of the 107 historical radiosonde data stations.

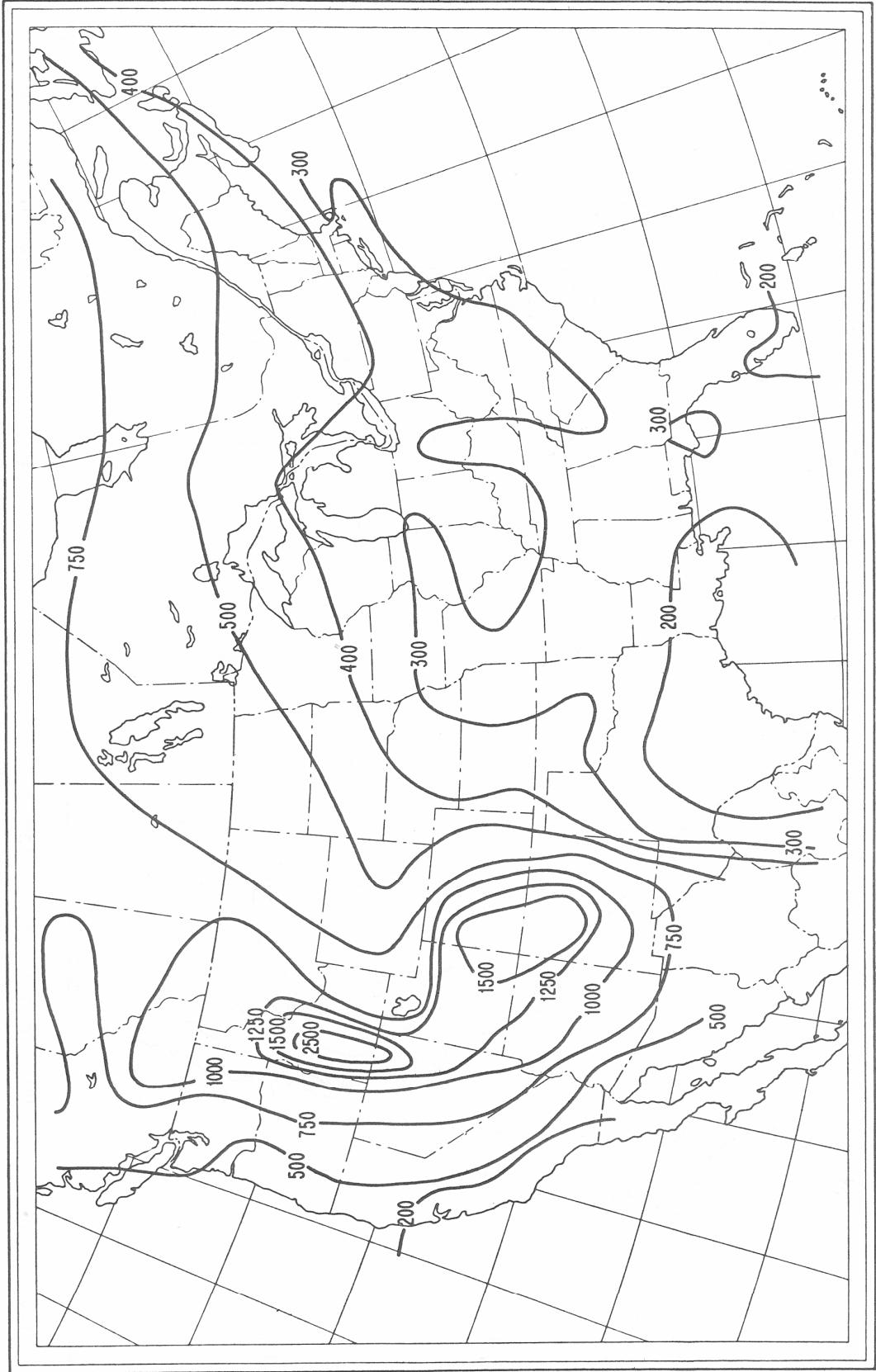


Figure 11. The median minimum trapping frequency,  $f_t(50\%)$  in megahertz.

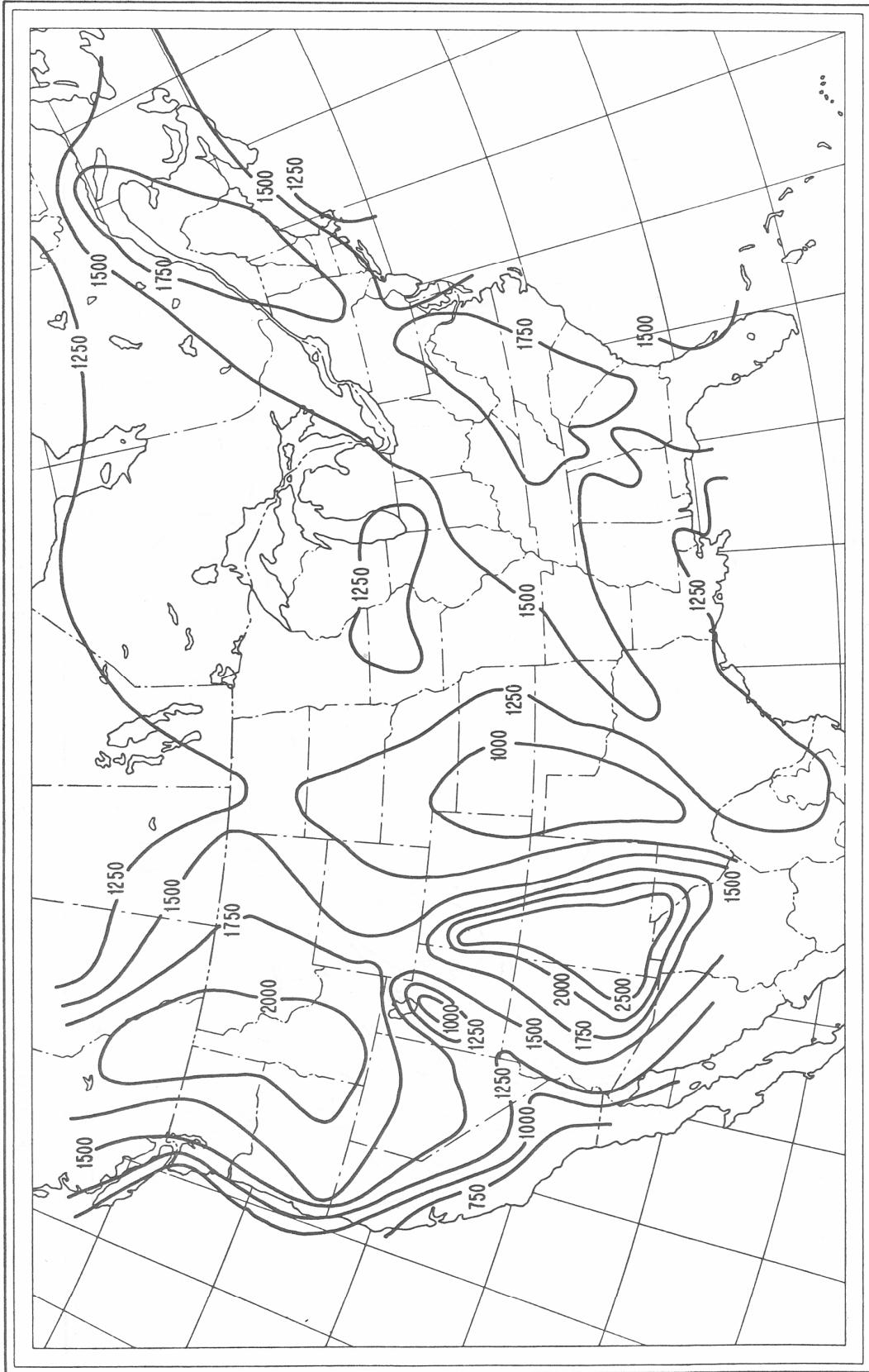


Figure 12. The optimum coupling elevation,  $h_0(50\%)$  in meters above the surface, expected for 50% of all elevated ducts.